Power scaling of picosecond thin disc laser for LPP and FEL EUV sources

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2016 International Workshop on EUV and Soft X-ray Sources

November 7-9, 2016 Amsterdam, The Netherlands

project supported by:

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Subjects

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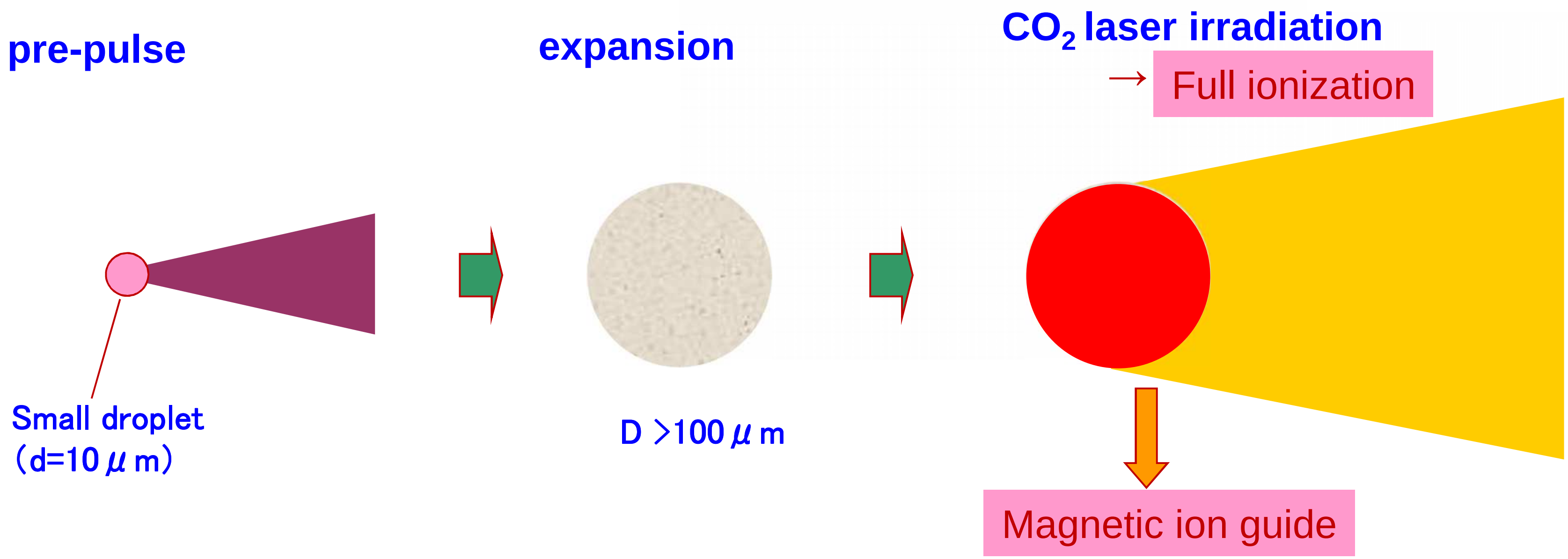
1. LPP EUV source and high repetition rate picosecond laser
2. FEL EUV source and high average power tunable picosecond laser
3. Single shot laser Compton X-ray source for Bioimaging and high pulse energy picosecond laser
4. Solution:Thin disc laser and Cryogenic laser

Optimization of pre-plasma conditioning

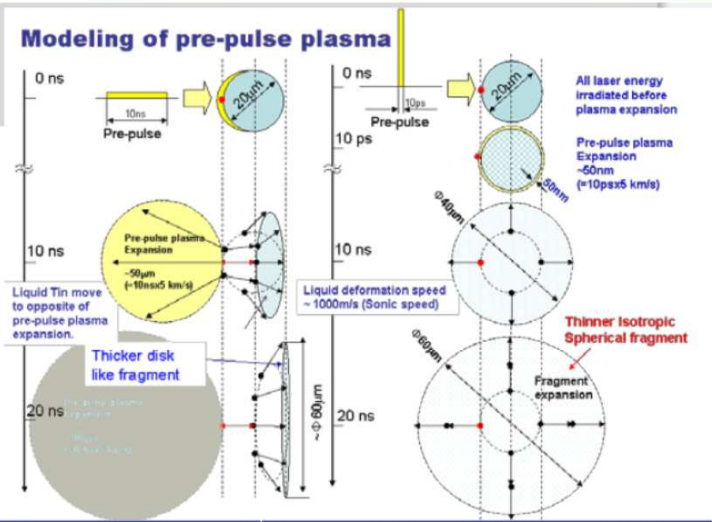


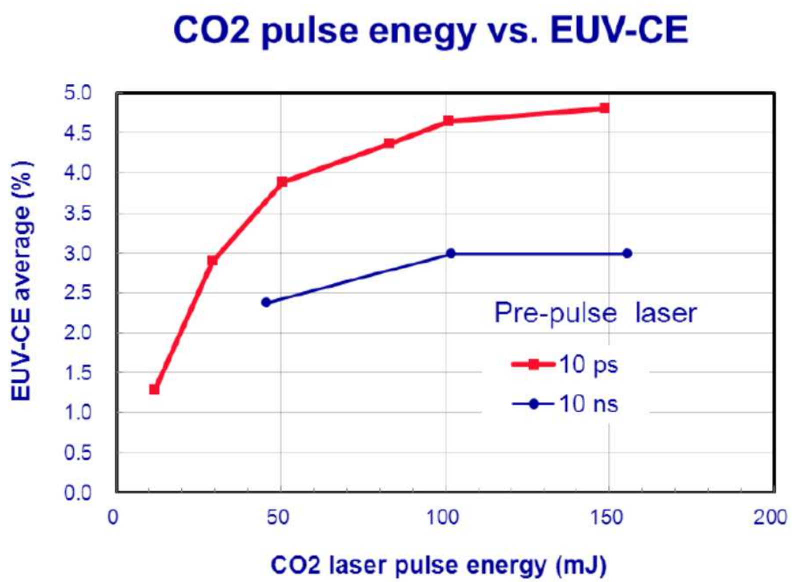
Optimize density, temperature and spatial distribution
for main pulse heating to achieve high EUV conversion efficiency
and ***full exhaust of Sn atoms : Beam quality is essential for higher CE***

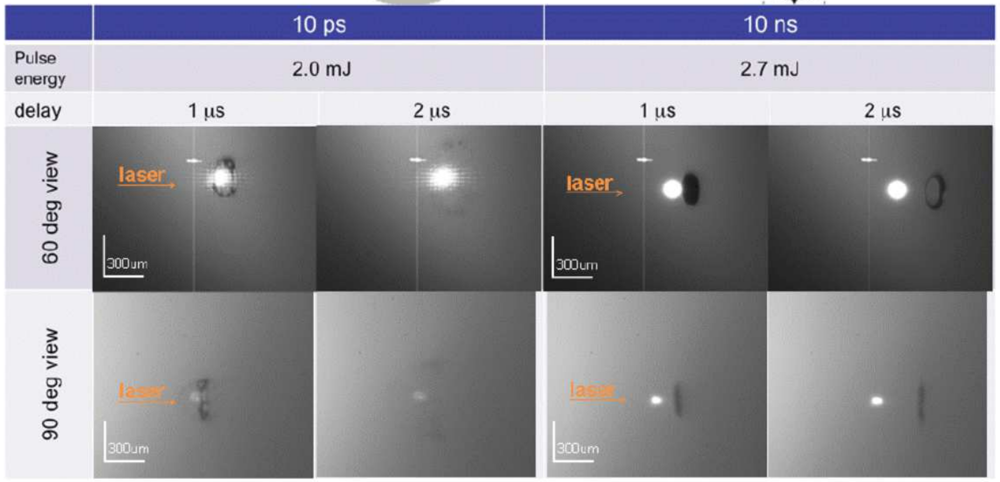
Mist tin bunch formation

③ Pico-second Pre-Pulse Technology (1)

- The mist shape of a picosecond pre-pulse is different from the nanosecond
- Nano-cluster distribution could be a key factor for high CE
- Champion data was 4.7% (in 2012).







Hollow Shell formation by picosecond pre-pulse

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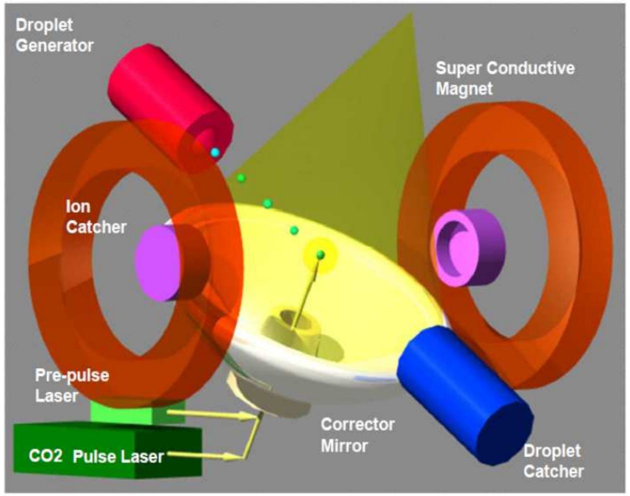


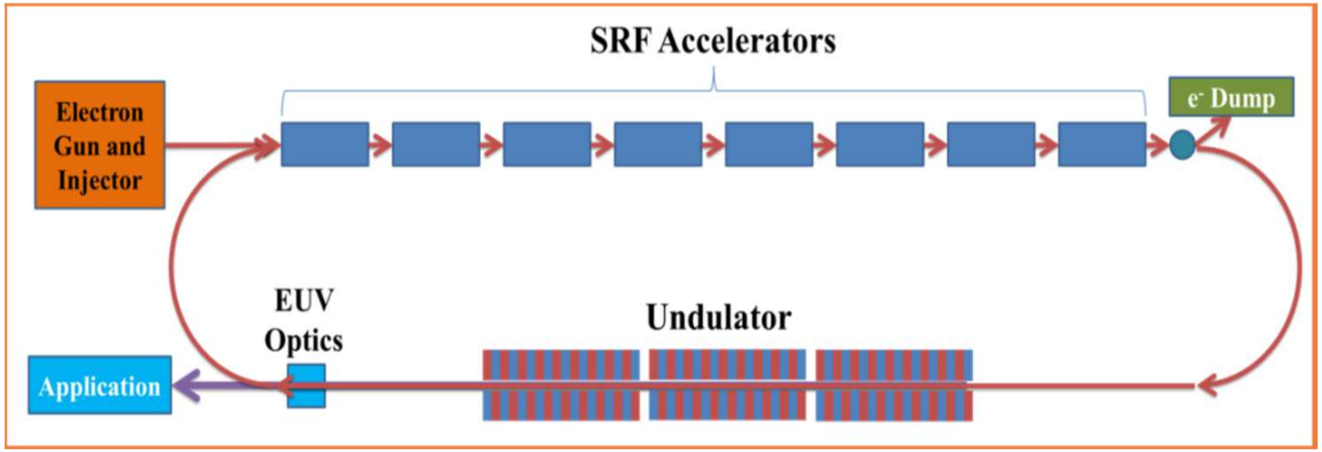
Time history of Sn nanocluster Hollow Shell formation

Configuration of LPP EUV source with picosecond pre-pulse

"Experimental and theoretical studies of tin droplets shaping by picosecond laser pre-pulses " (S24)
International Workshop on EUV and Soft X-ray Sources
November 9-11, Dublin, Ireland
Slava Medvedev et al, EUV Labs, Russia

Proposal : ERL (Energy Recovery Linac) FEL for >kW 13.5nm source

From "Free-electron laser extreme ultraviolet lithography: considerations for high-volume manufacturing, Erik R. Hosler" presented at SPIE Advanced Lithography 2015



($M)		10x 250 W LPP Sources	EUV ERL FEL (10x Scanners Powered @ 1 kW)
Cost to Power 10 Scanners	OpEx	85	23
	CapEx	256	240
	Total Cost First Year	>341	263
	FEL CapEx Savings		16
	FEL Yearly OpEx Savings		62
Uptime Per Source		Target 90%	~100%
Average Exposures Per Day (10 Scanners, Dose: 25 mJ/cm^2, 120 Fields)		13,280	29,700

Metal photocathode for long lifetime and stability

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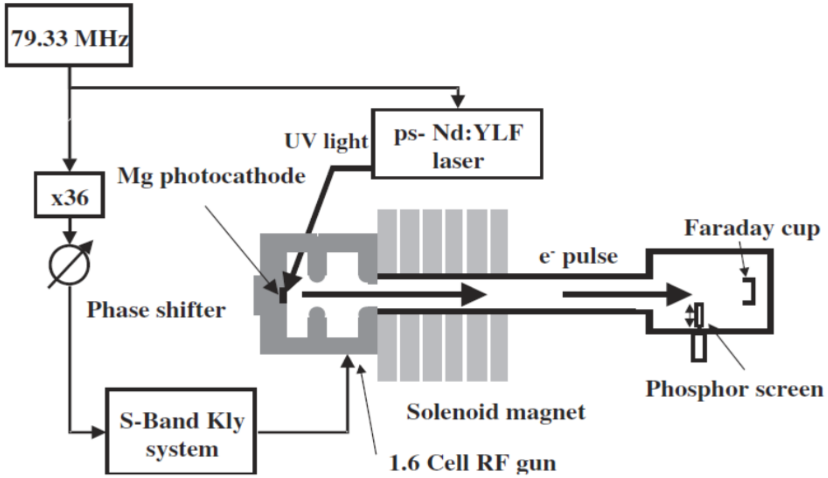

Fig. 3. Schematic diagram of the Mg cathode performance test system.

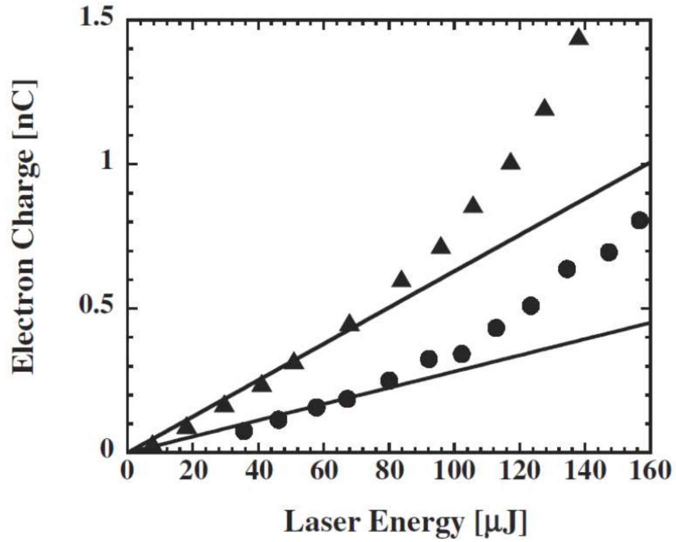

Fig. 5. Emitted electron charge from the Mg cathode as a function of the laser (349 nm) energy before (●) and after (▲) laser cleaning. The lines represent the best fit of the data at the laser energy <80 μJ.

100μJ x 1MHz = 100W, several ps at 3HG

Jpn. J. Appl. Phys. Vol. 42 (2003) pp. 1470–1474
Part 1, No. 3, March 2003

Quantum Efficiencies of Mg Photocathode under Illumination with 3rd and 4th Harmonics Nd: $LiYF_4$ Laser Light in RF Gun

Terunobu NAKAJYO, Jinfeng YANG, Fumio SAKAI and Yasushi AOKI

Temporal smoothing of FEL pulses by UV picosecond laser seeded HGHG

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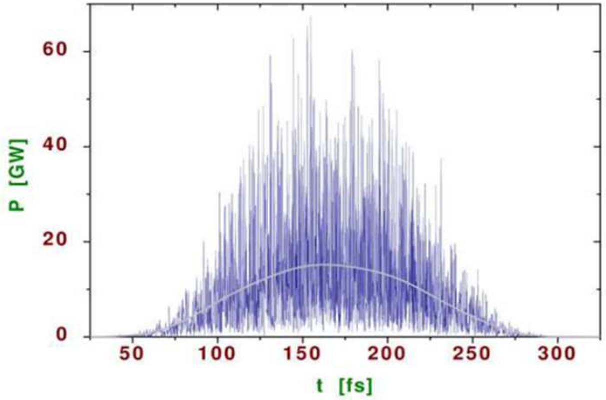
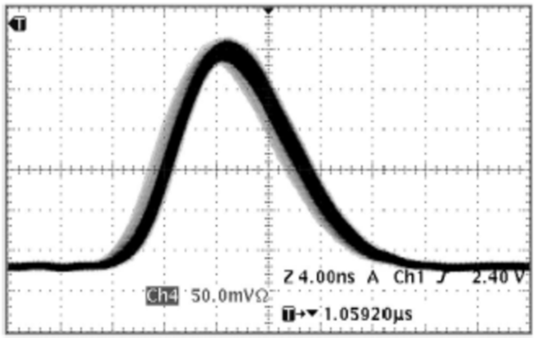
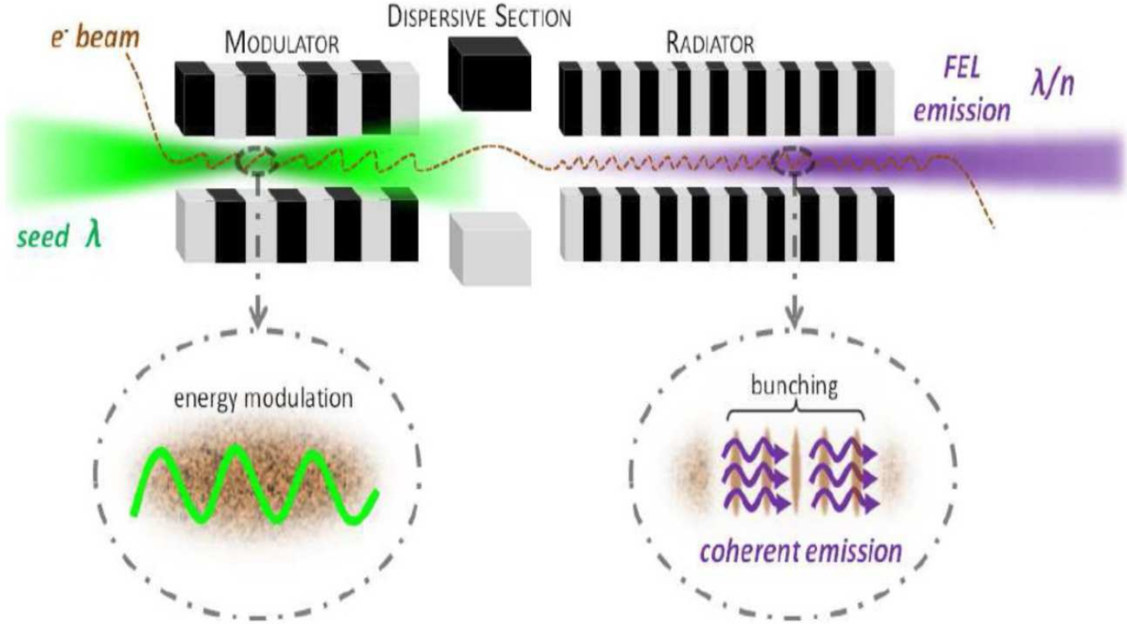


SASE FEL pulse shape



Smoothed pulse shape

100µJ x 10MHz = kW, 1ps, 4HG



Schematic of the working principle of a HGHG free-electron laser.

Chirped pulse amplification in X-ray free electron lasers
Hugo Ducasa et.al. SPIE 9585-15, San Diego 2015

Single shot bio imaging by laser Compton X-ray source

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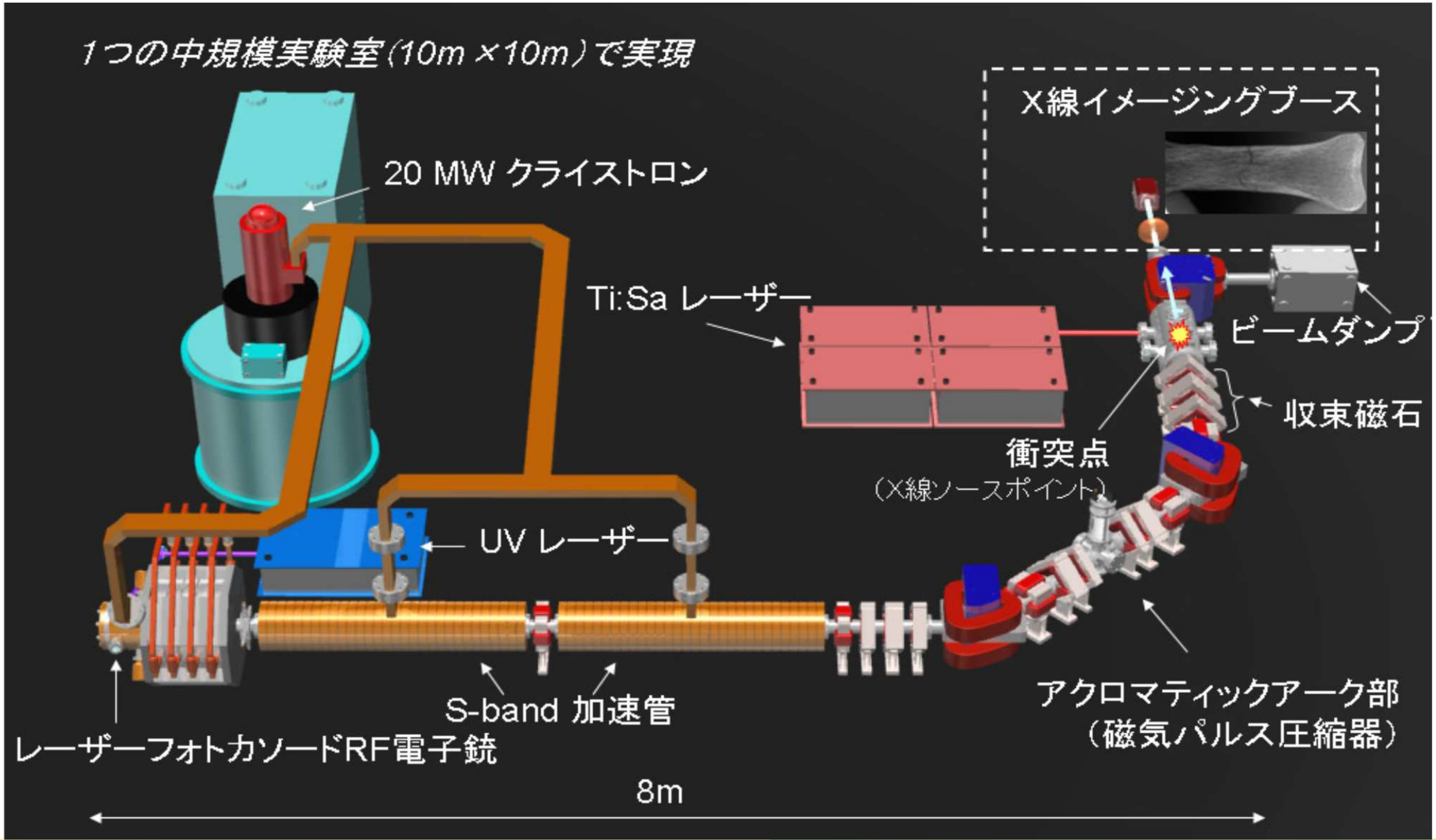

Temporal spatial multiplexing of medium energy laser pulses for single shot imaging

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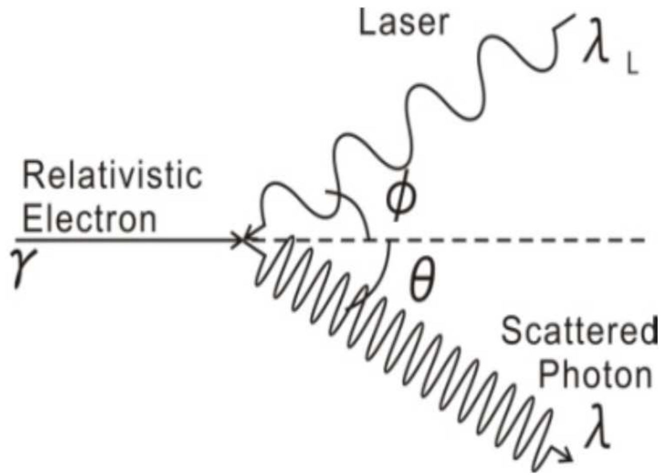
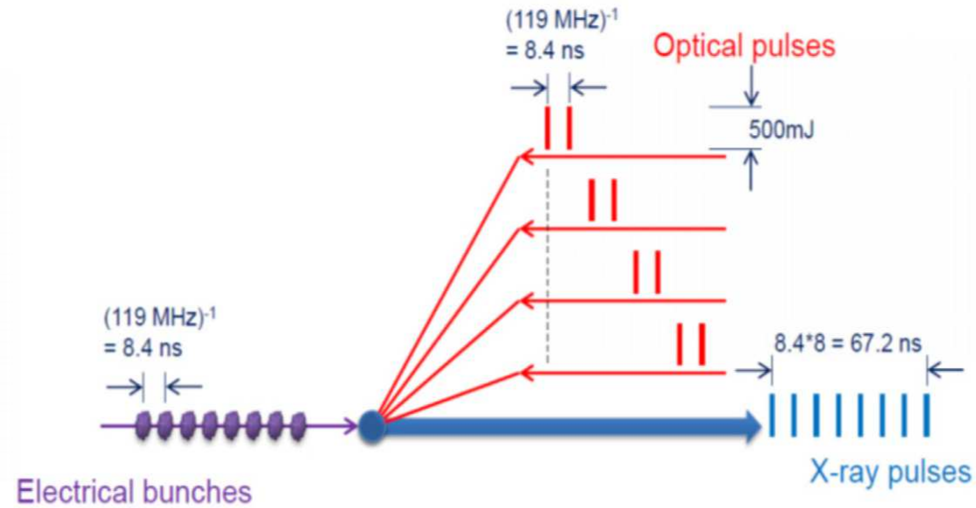


Laser Compton configuration



Temporal-spatial multiplexing

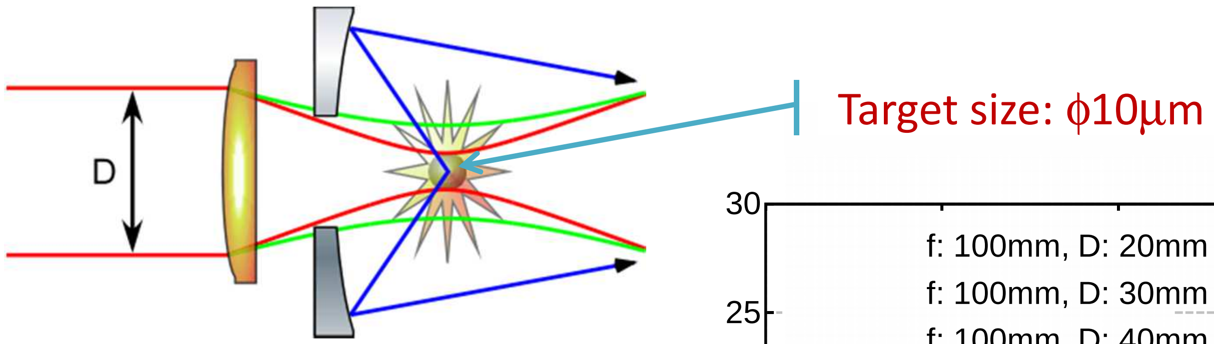
$$N_0 \propto \frac{\sigma_c N_e N_p}{4\pi r^2}$$

R=10μm in single focus

X-ray photon number

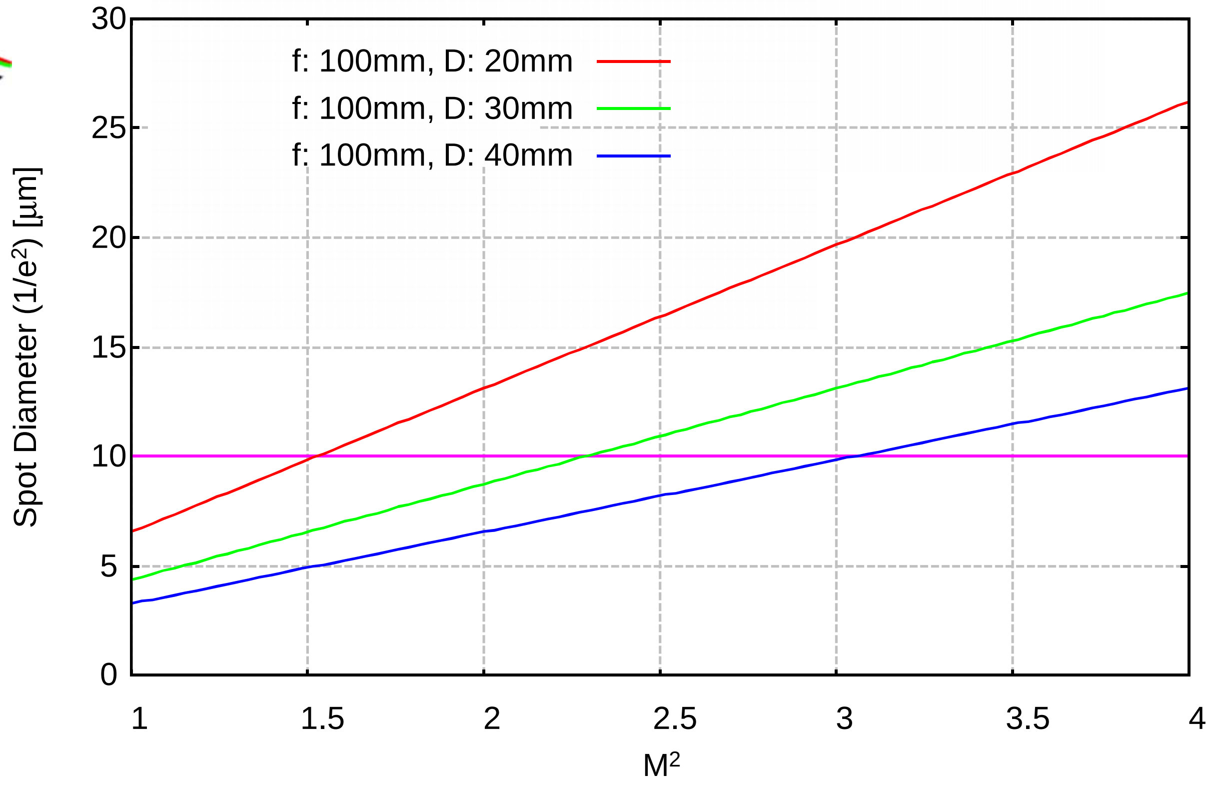
Module pulse energy	>500mJ/ps
Module number	8 units
Multiplexed energy	4 J
Micro pulse time interval	8.4ns (119MHz)
Macro pulse width	~60ns

Focusing Property of Laser and M^2



Target size: 10µm
Focal length of lens: f=100mm

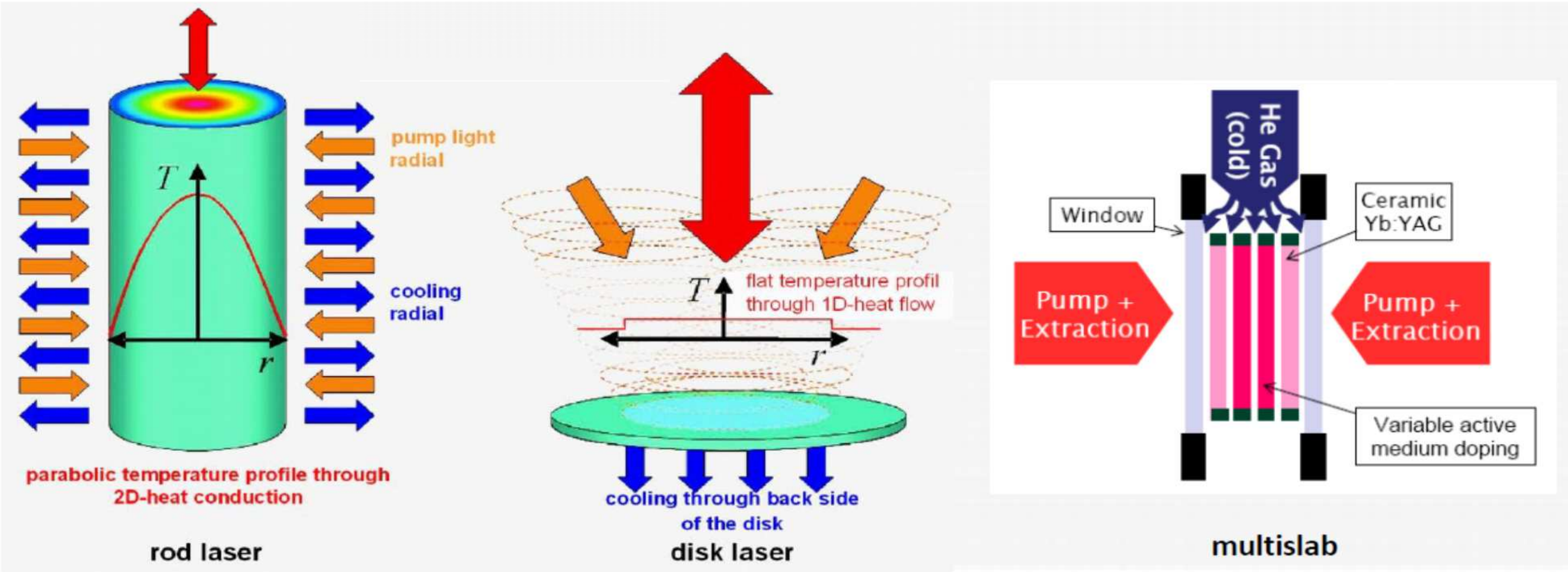
- D=20mm
  - M^2<1.5
- D=30mm
  - M^2<2.3
- D=40mm
  - M^2<3



eli beamlines

Efficient cooling in SS lasers

10 Hz rep. rates Pulse energy 10J	kHz rep. rates kW average power	10 Hz rep. rate High pulse energy >100J



Courtesy T. Metzger (MPQ Garching)

Courtesy K. Ertel and J. Collier (RAL/STFC)

Wavefront distortion in solid state laser amplifier

Optical path difference (OPD)

Opto-mechanical parameters　　Temperature field

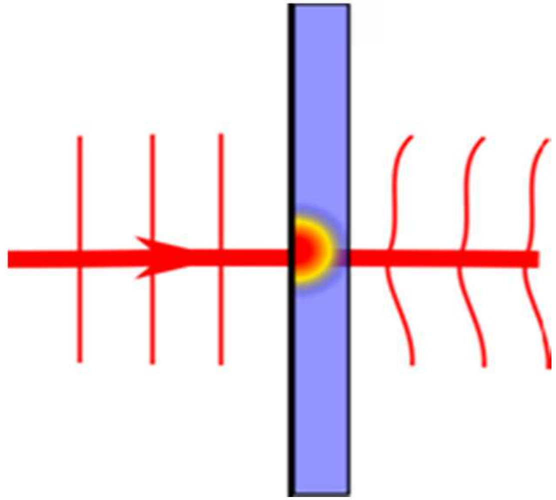
$$\mathrm{OPD} = \left[\frac{\partial n}{\partial T} + \alpha(1+\upsilon)(n+1)\right] \cdot \int_{z=0}^{d} \Delta T(x,y,z)\,\mathrm{d}z$$

Thermo-optic coefficient

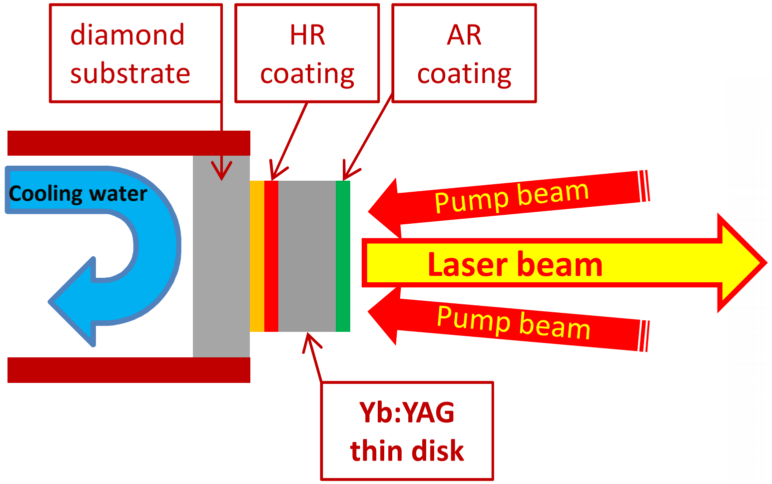
Thermal expansion coefficient

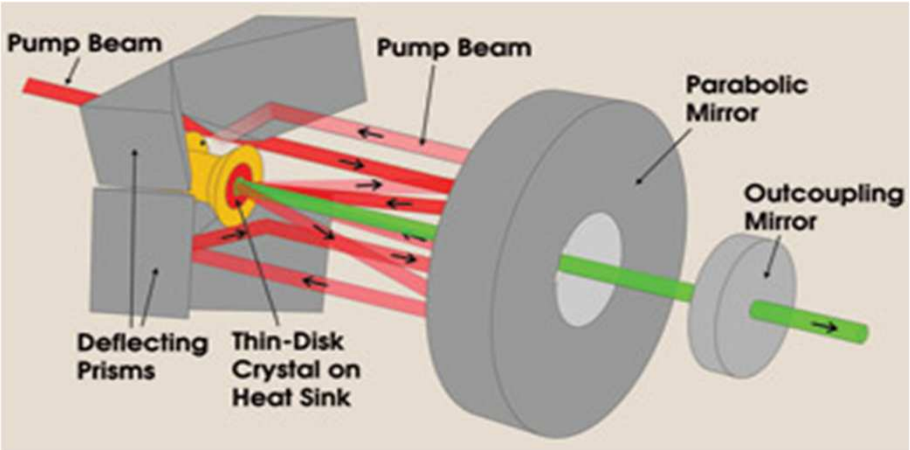
Poisson coefficient

Refraction index



Yb:YAG thin-disks for high average power amplifiers

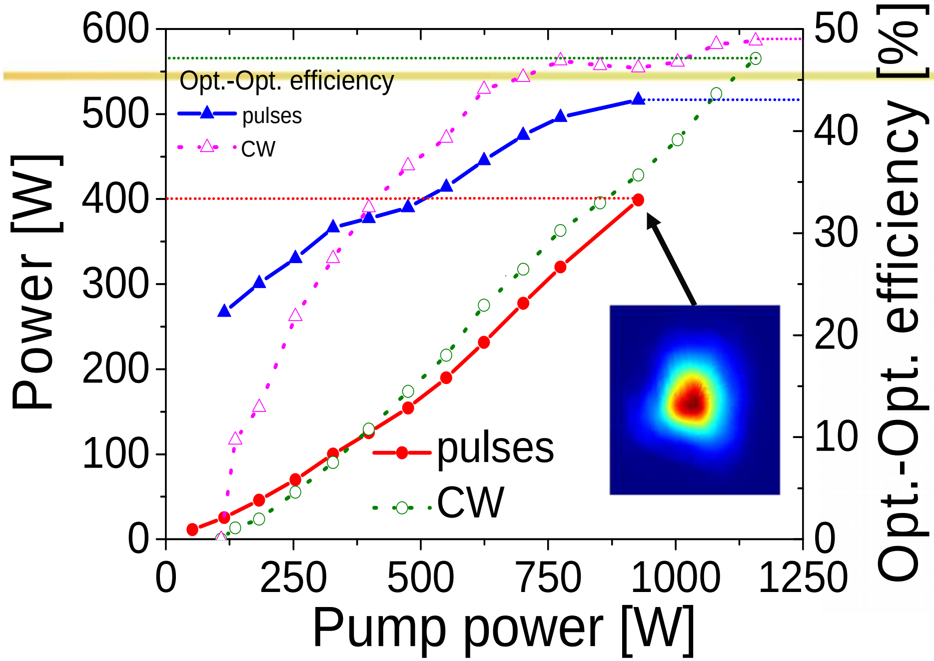


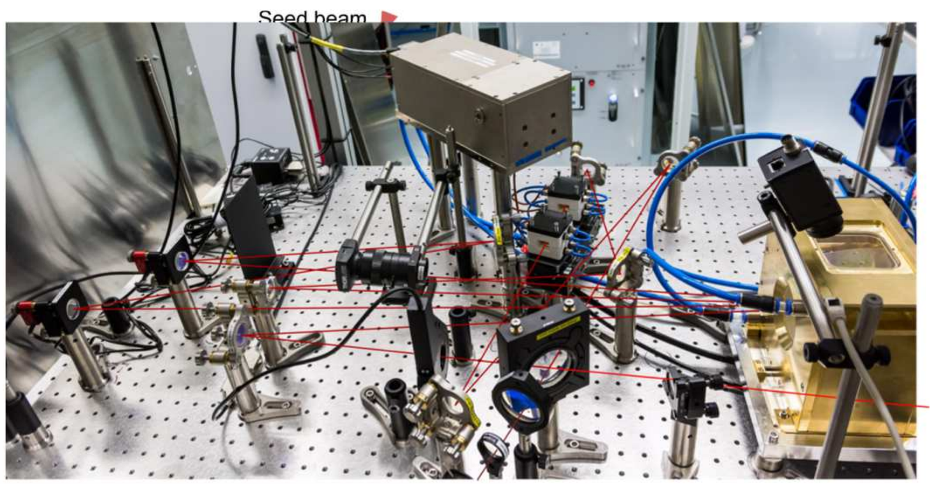


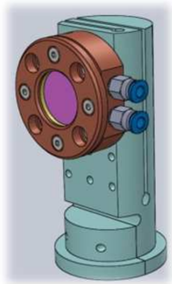
Thin disk parameters:

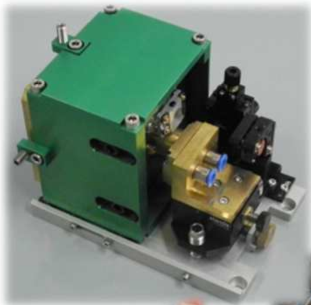
- 220 μm thickness
- 10 mm diameter
- 7.2 at.% Yb^{3+} doping
- water-cooled
- radius of curvature 3.9 m, increases under intense pumping - careful cavity design
- low gain → regenerative amplifier

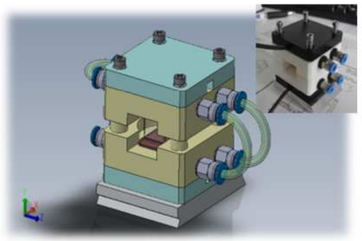
PERLA C



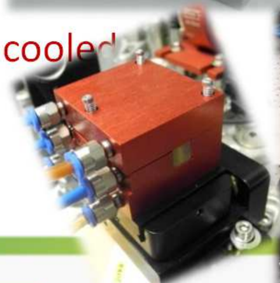


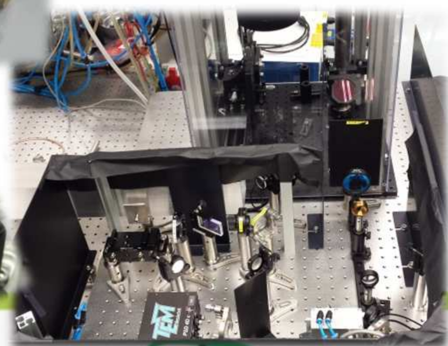






- Output energy 4 mJ at 100 kHz
- >0.5 kW in CW mode
- High opt. efficiency >43% in pulse mode
- Good beam quality M^2 1.3 and 1.4 in x, y
- BBO Pockels cell (2x 10x10x24mm BBO)
- In-house development of components (PC holder, compressor, cooled mirrors, laser head to 50 W)





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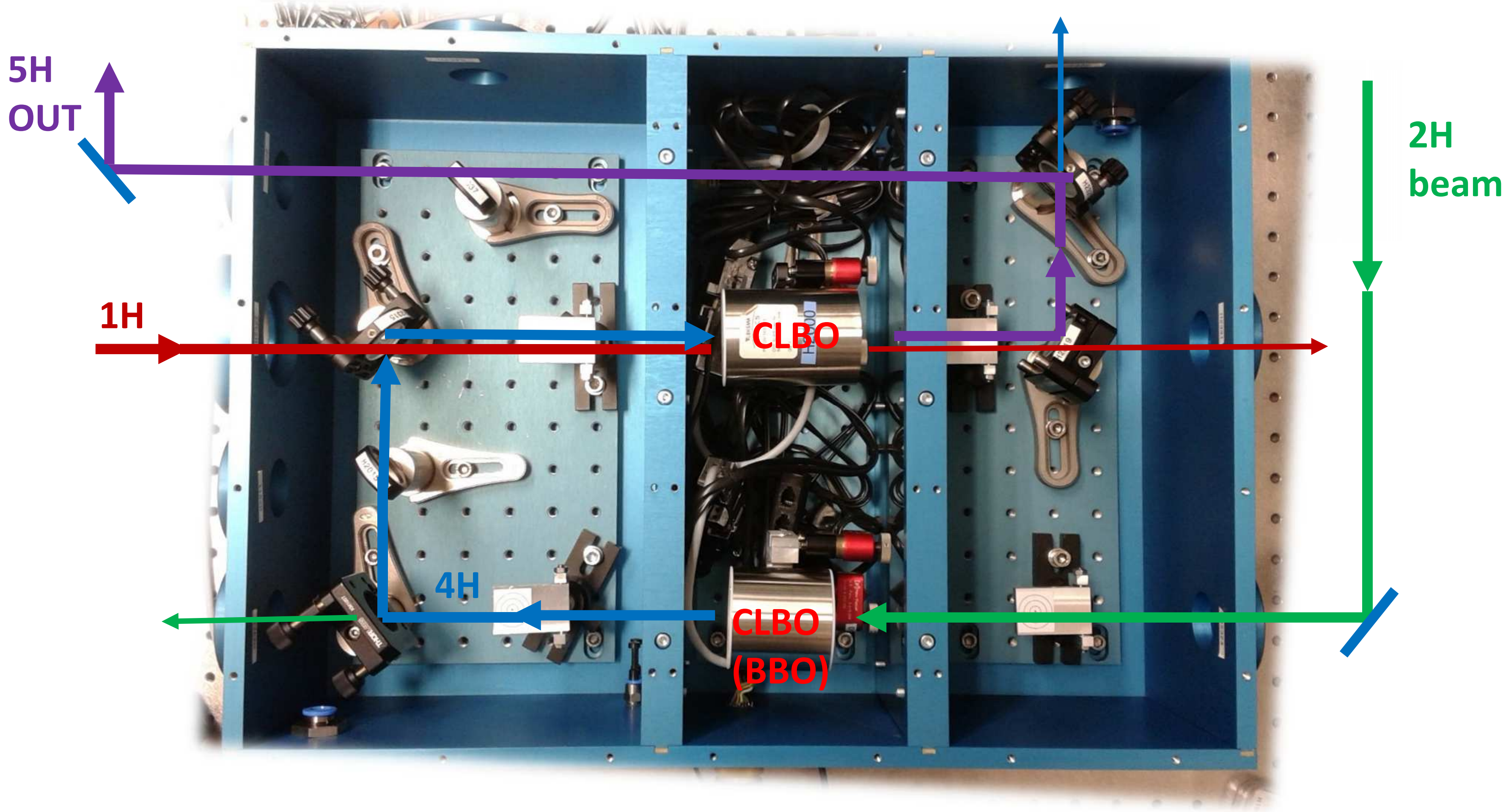
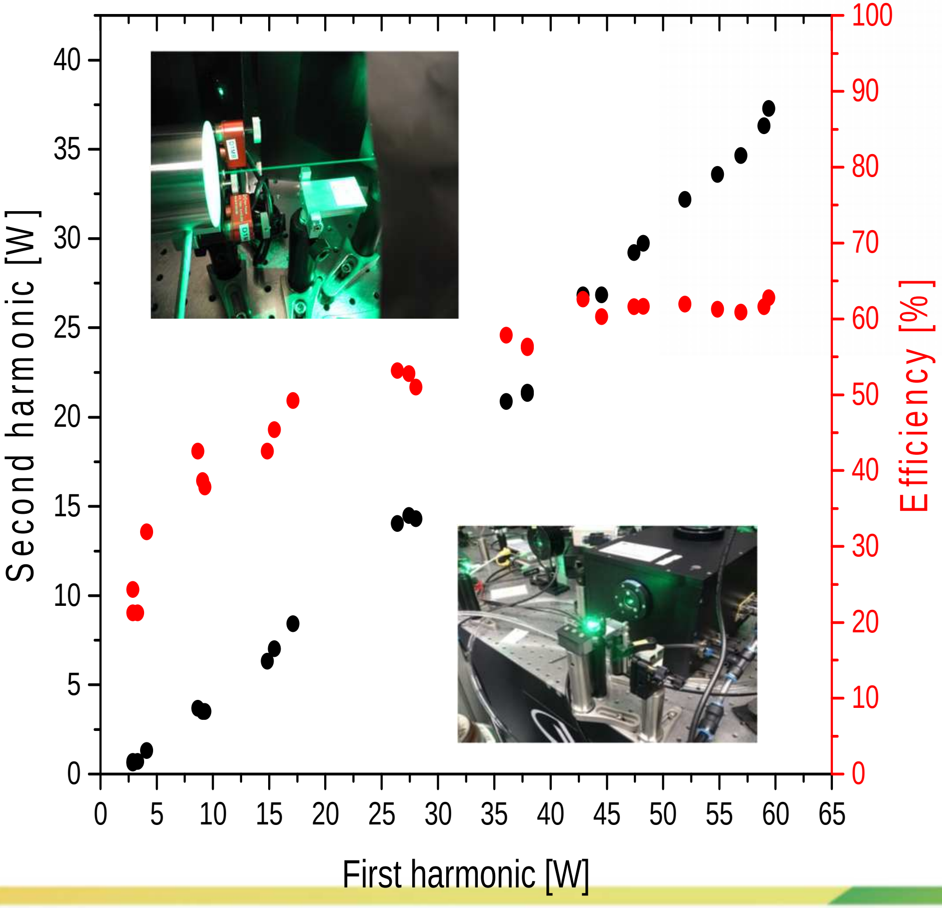
UV~DUV generation   4HG & 5HG (1ω + 4 ω)

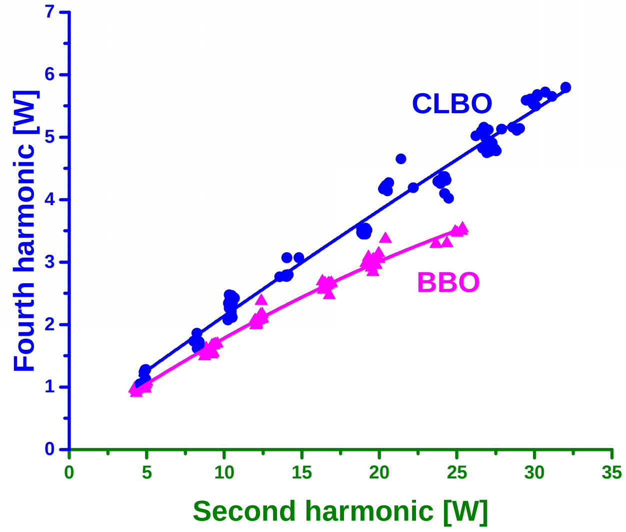


2^{nd} and 4^{th} harmonic generation

- 6 W in fourth harmonic (**60µJ, 1ps, 100kHz**) reached !

paper submitted





4H/2H conversion:

CLBO ….. 18%

BBO ……. 14%

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1.4 kW output operated at 1 MHz, multipass in air

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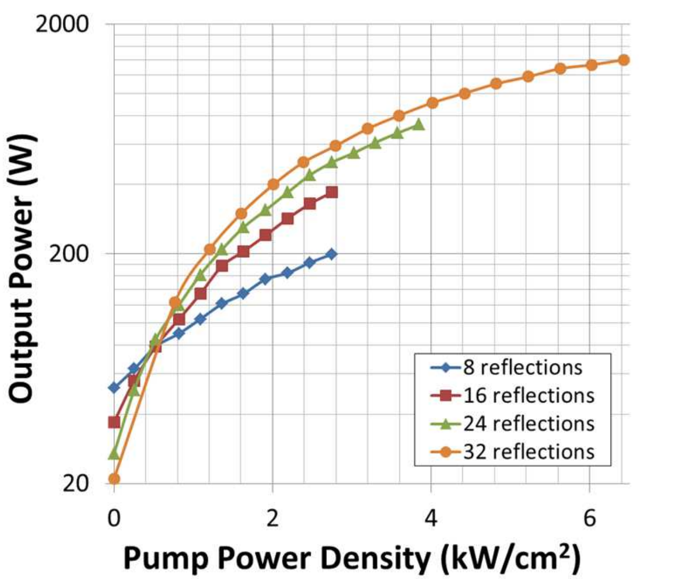
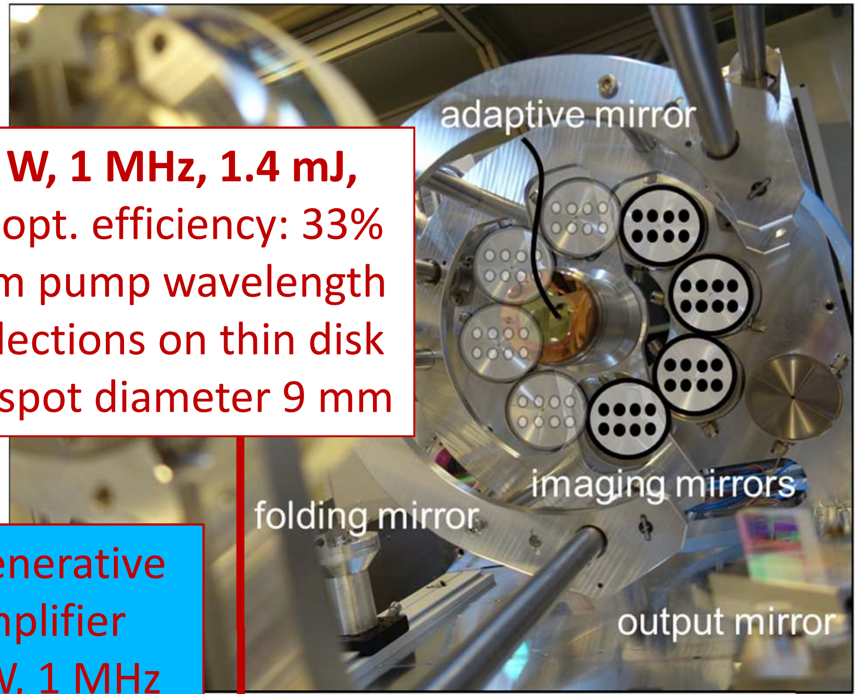
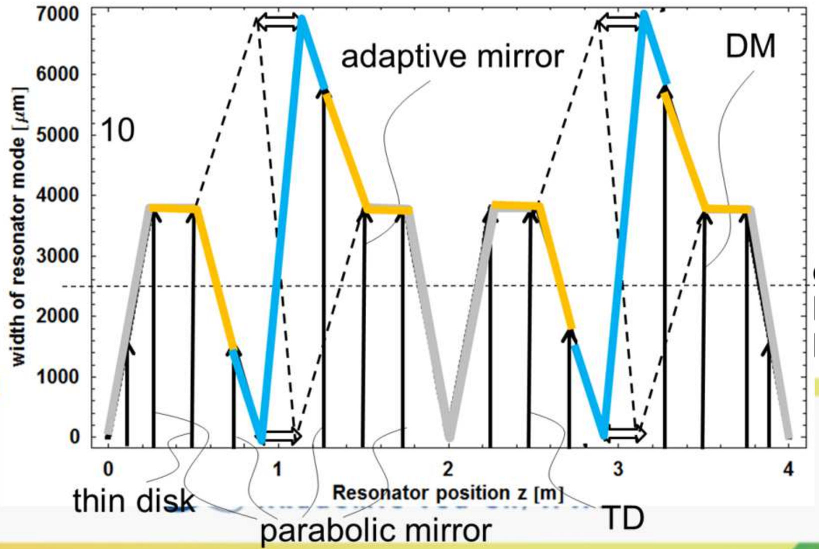
Power of light

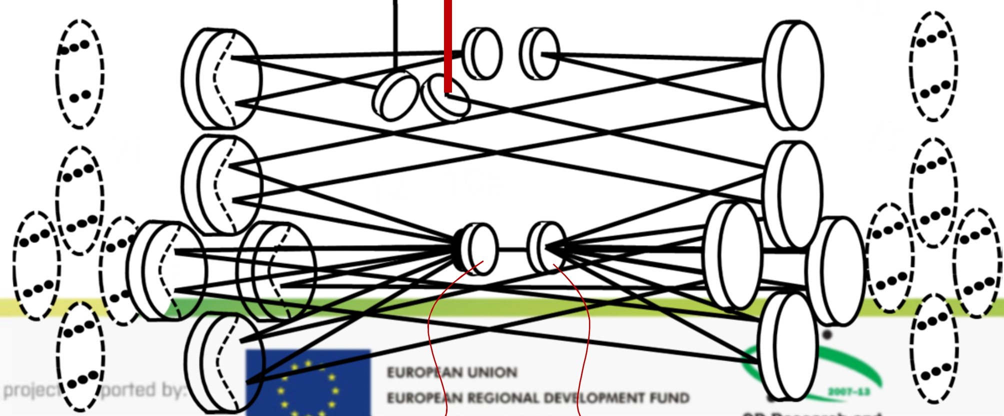


1400 W, 1 MHz, 1.4 mJ,
opt. / opt. efficiency: 33%
940 nm pump wavelength
32 reflections on thin disk
pump spot diameter 9 mm



Regenerative amplifier
92 W, 1 MHz



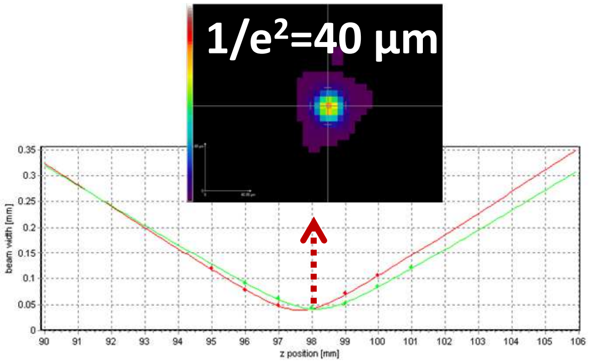


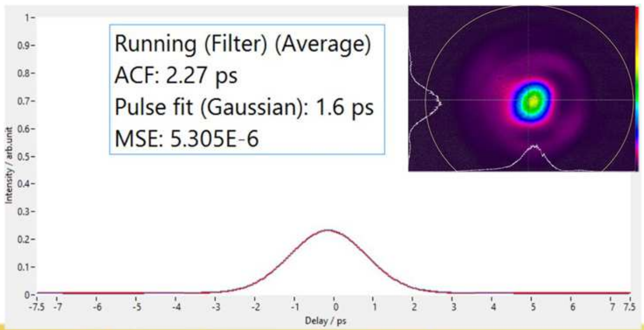
High energy output obtained from HERA

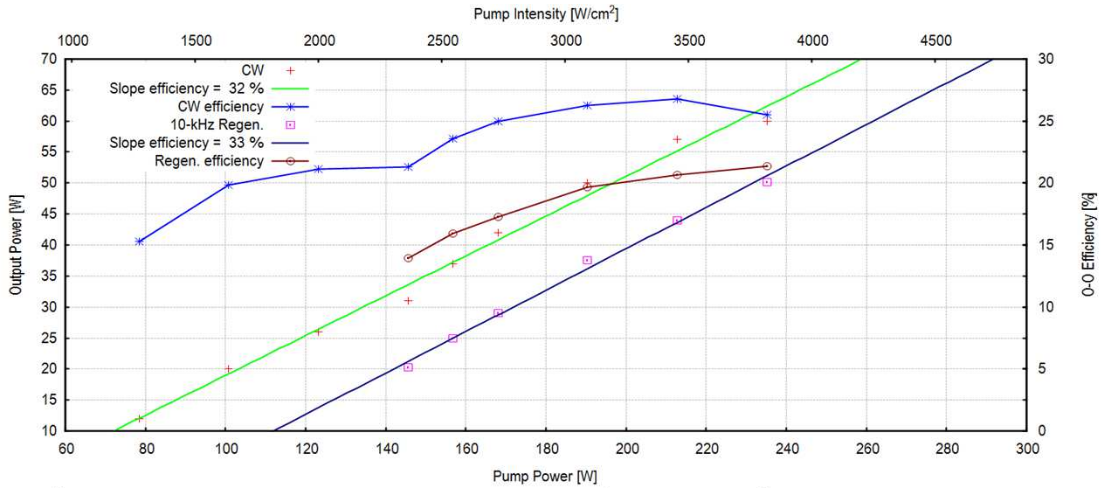
Power of light

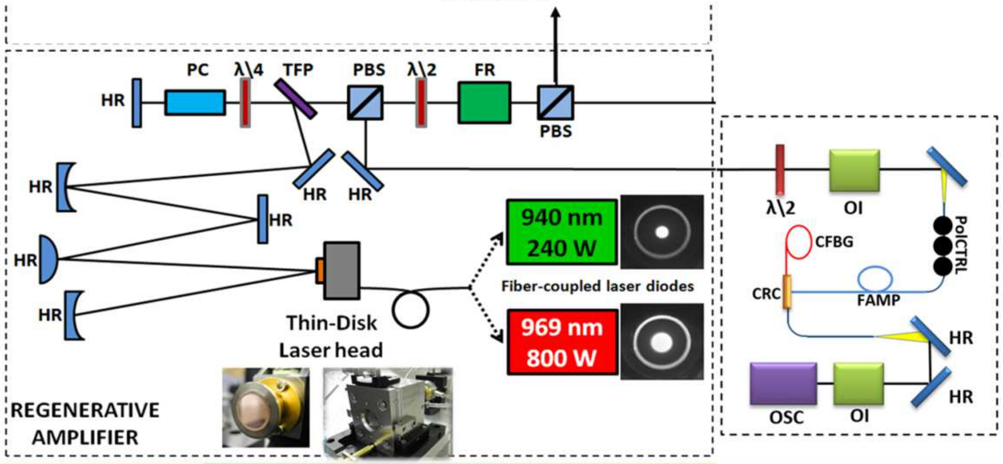
45 mJ at 1 kHz, 465 W@50%DC- 500 µs at 969 nm, 20 % O-O eff.

M^2	
Horizontal	Vertical
1.25	1.23









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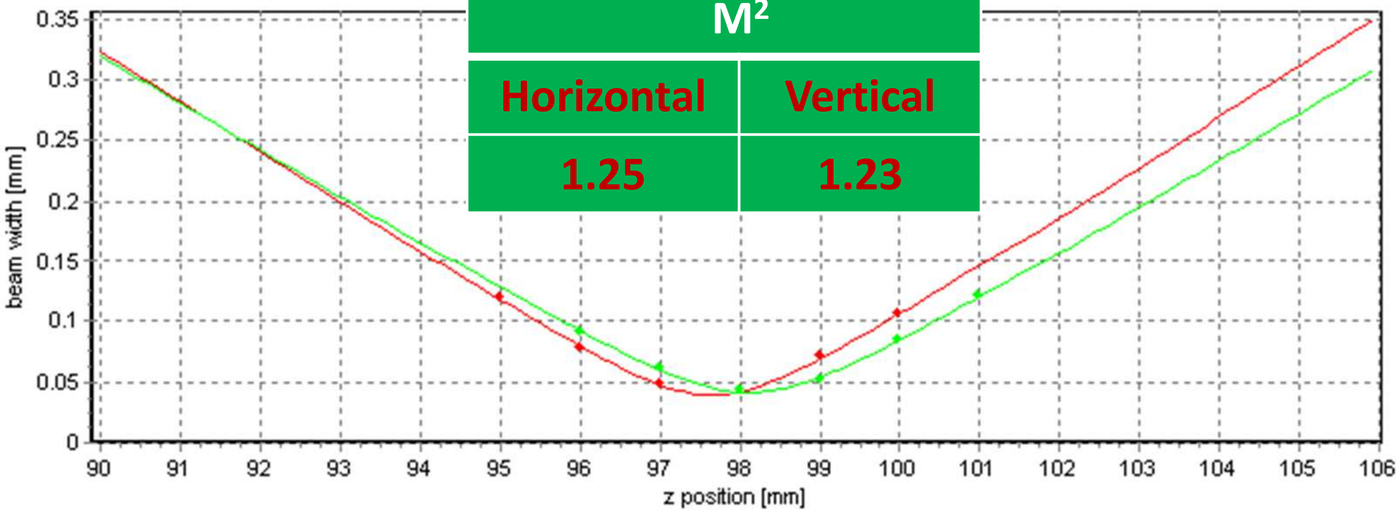
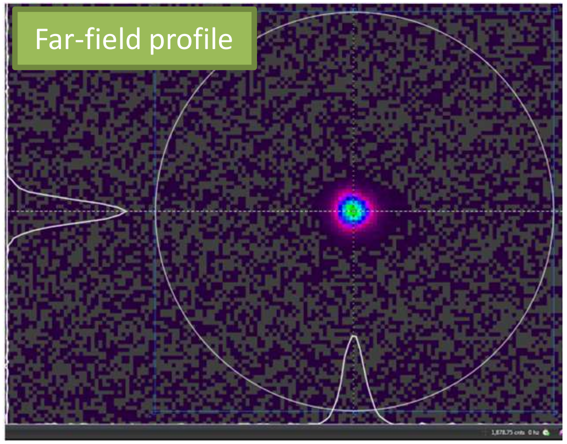
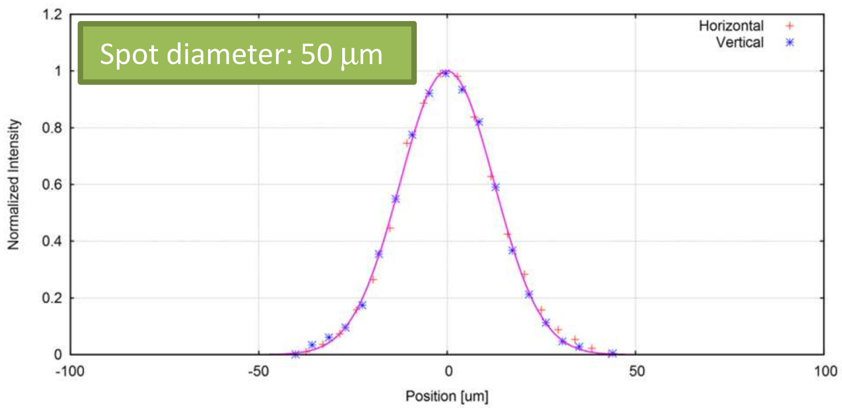
M^2 measurement of HERA

M^2	
Horizontal	Vertical
1.25	1.23







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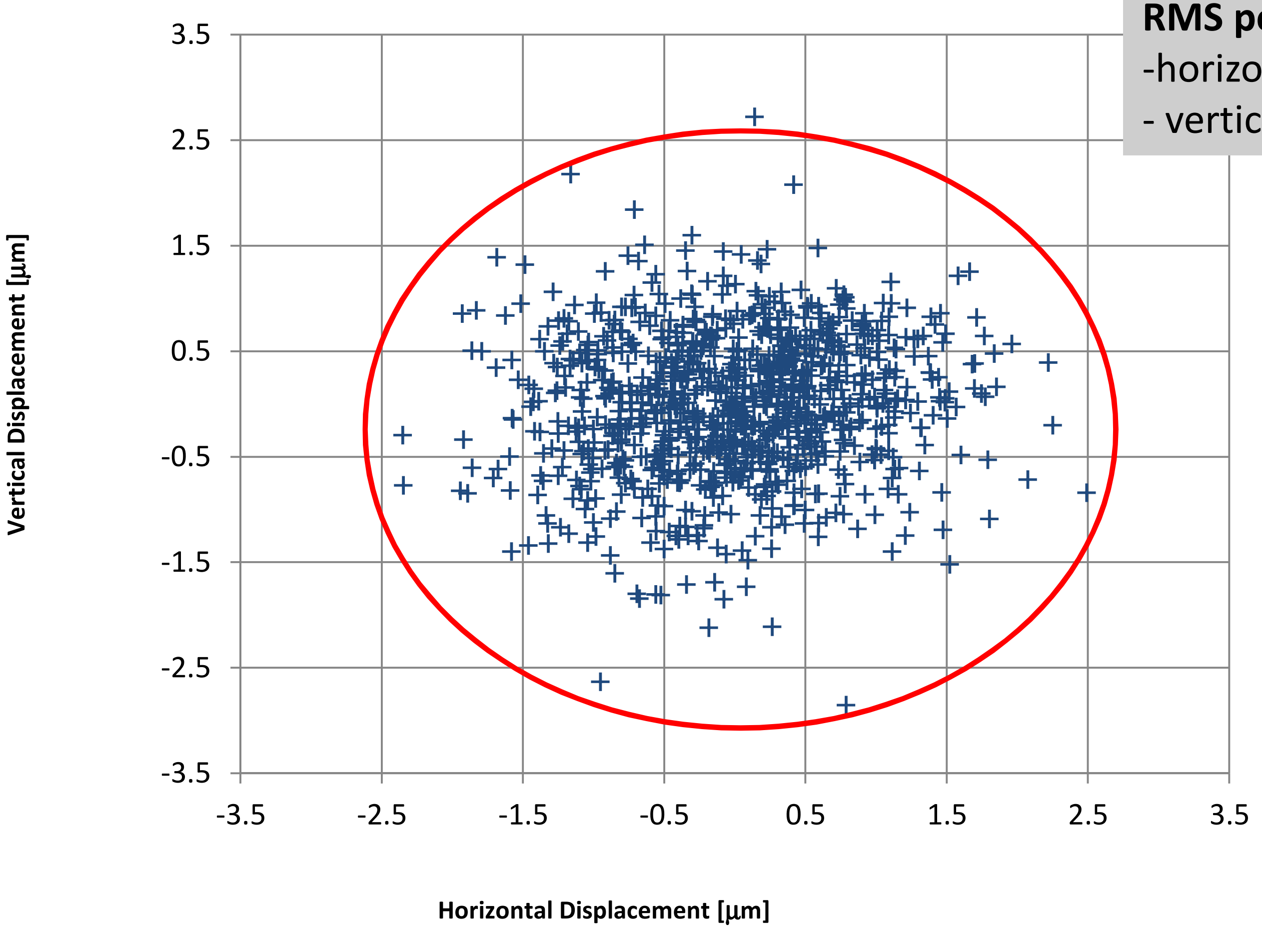
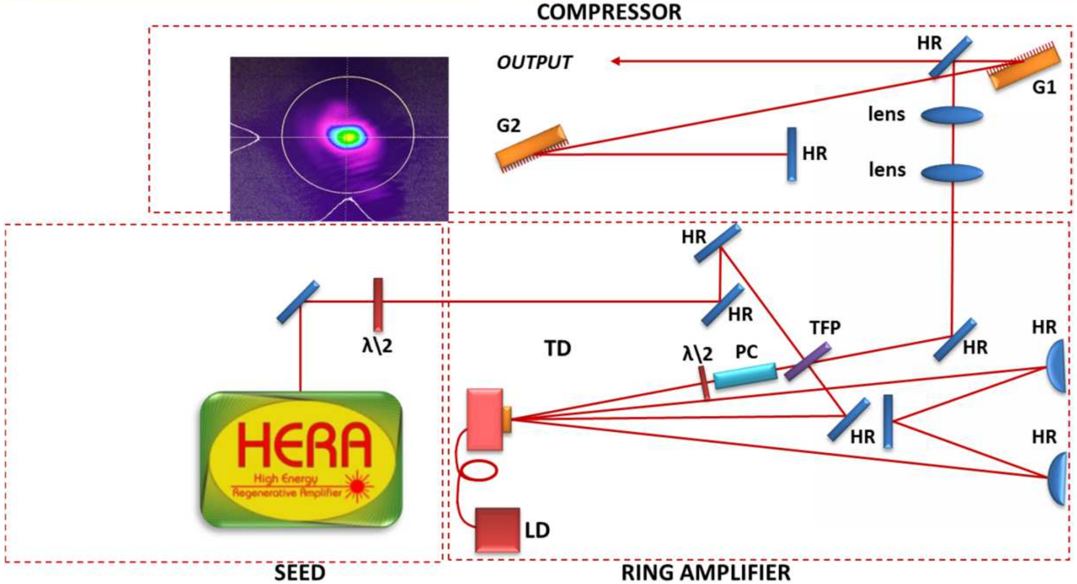
High beam pointing stability

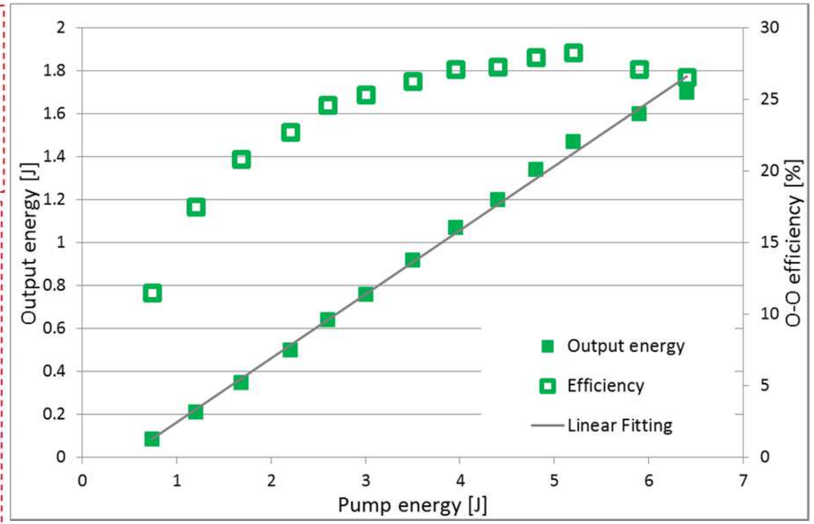


RMS pointing stability:
-horizontal: **3.8-µrad**
- vertical: **3.3-µrad**

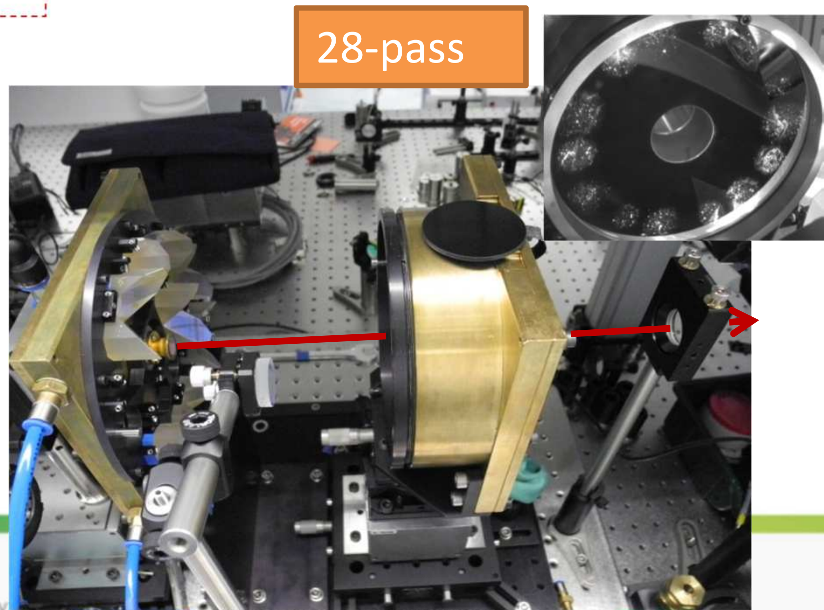
Measurement time: **15 min**

Over 1-J Output From HiLASE Thin Disk





28-pass



Yb:YAG as multi pulse amplifier for less ASE effect

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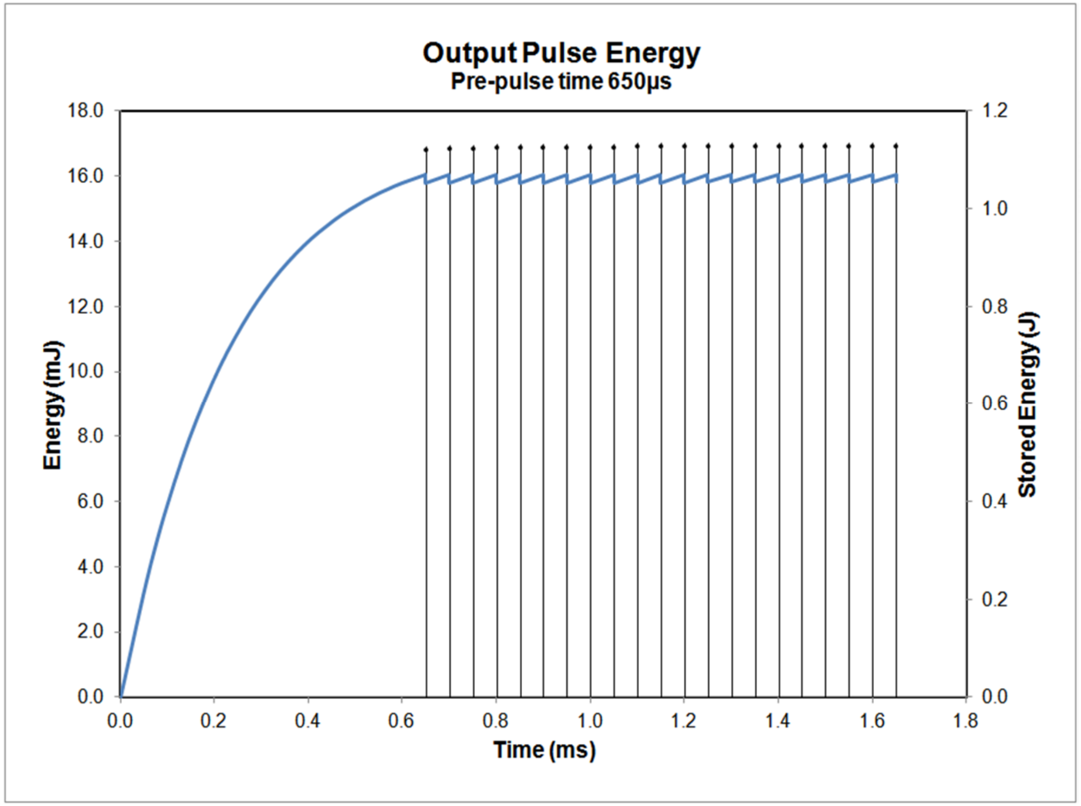
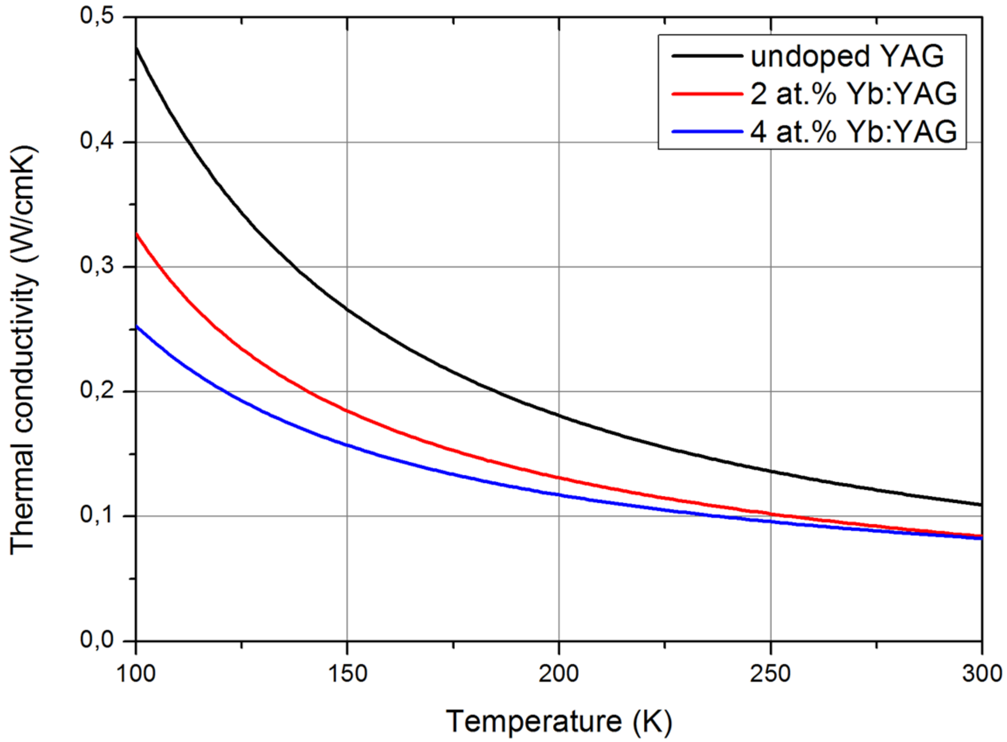
Power of light



1. Higher extraction efficiency
2. Minimize mirror distortion
3. R = 10μm focus
4. Pointing stability < μm
5. No nonlinear Compton process

10J : 100mJ x 100 pulses, MHz (0.1ms bunch length)

Thermal conductivity as a function of temperature for Yb:YAG



Cryogenic laser : Model and Parameters

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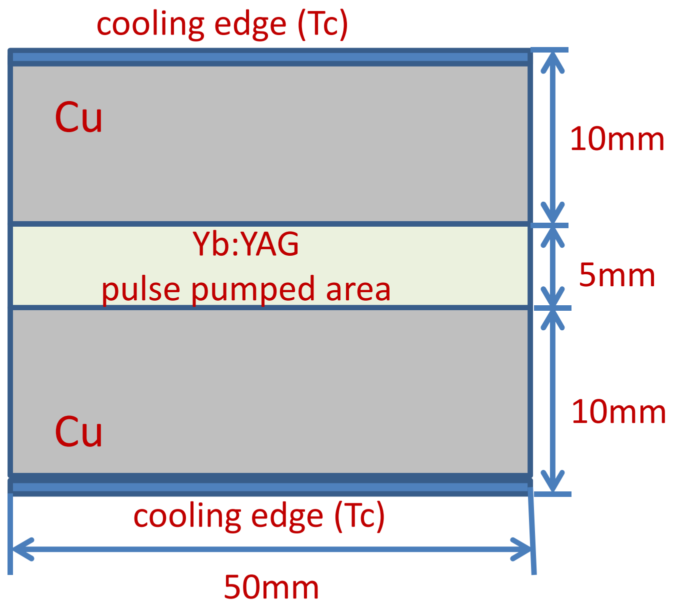
2D slab model



dimension of Yb:YAG: 50mm x 5mm x 20mm

dimension of Cu: 50mm x1 0mm x 20mm

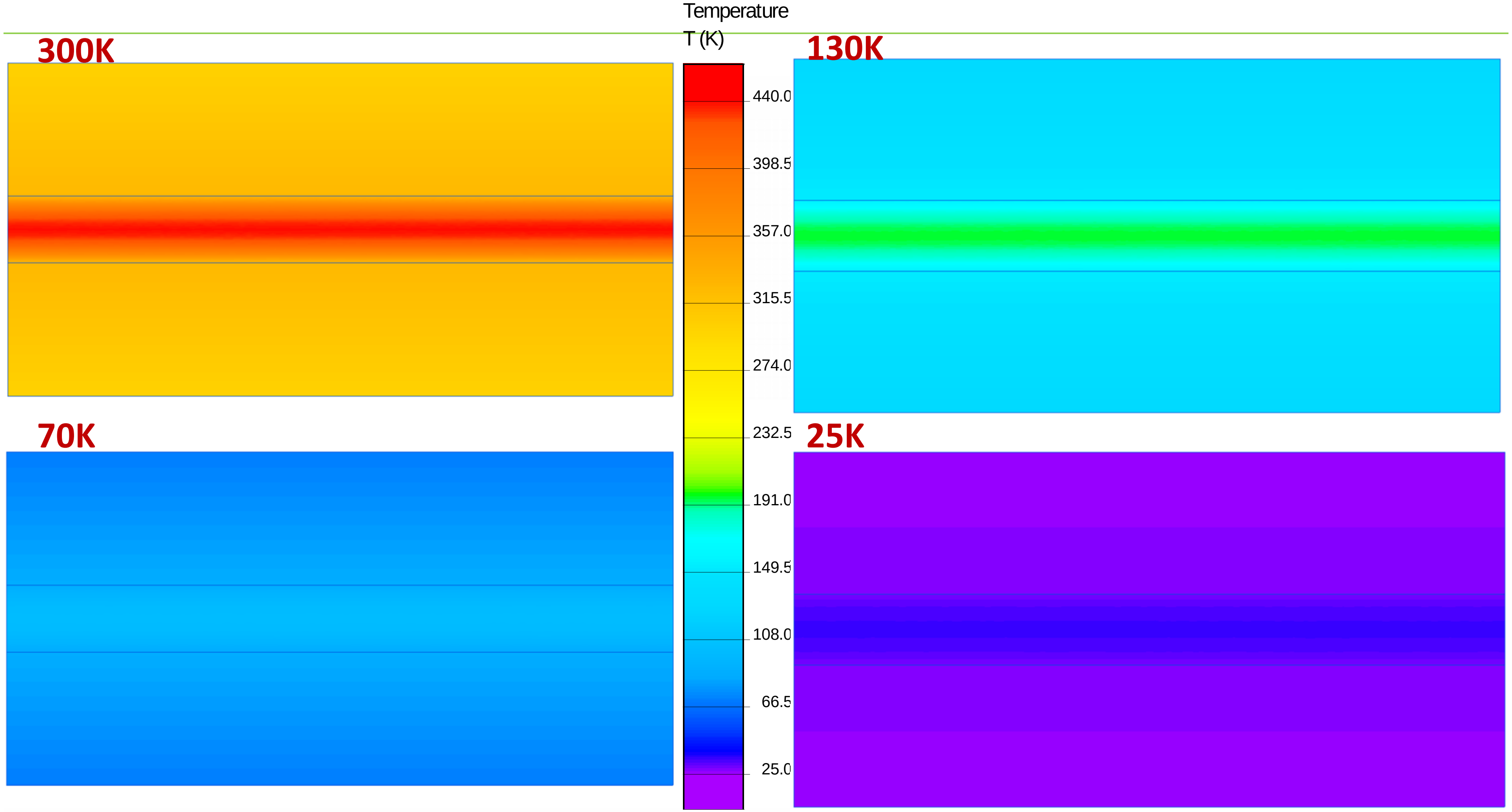
pump power transfered to heat – 4kW/cm^2

pulse duration 1ms, frequency 100Hz

1% at concentration of Yb3+ in YAG

	Yb:YAG		**Cu**	
Tc [K]	**thermal conductivity [W/mK]**	**specific heat [J/kgK]**	**thermal conductivity [W/mK]**	**specific heat [J/kgK]**
300	11	625	401	390
130	30	250	450	300
70	95	150	647	170
25	600	100	7600	10

Results comparison – the same scale



Setup for wavefront measurement of the amplified beam
2 passes through the gain medium

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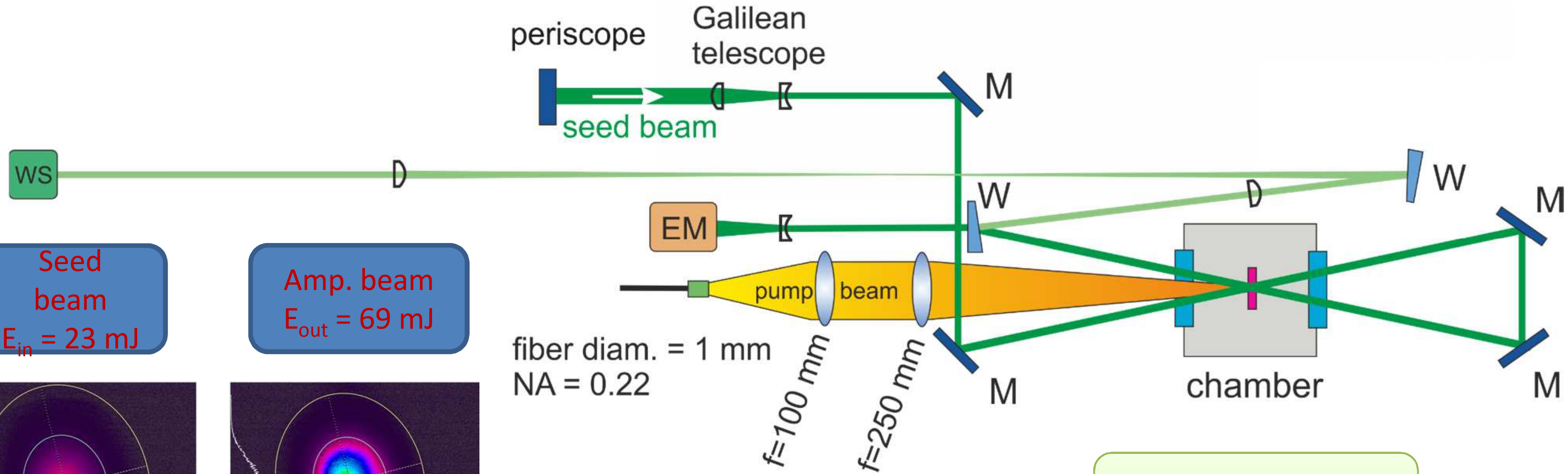
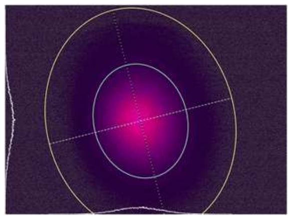
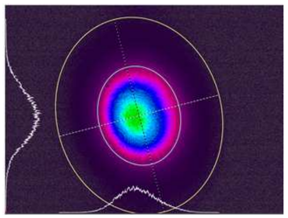


Seed
beam
E_{in} = 23 mJ

Amp. beam
E_{out} = 69 mJ





f = 40 Hz, T = 160 K

3 at. % Yb:YAG
D = 10 mm, L = 2 mm

Pump spot diam. = 2.5 mm

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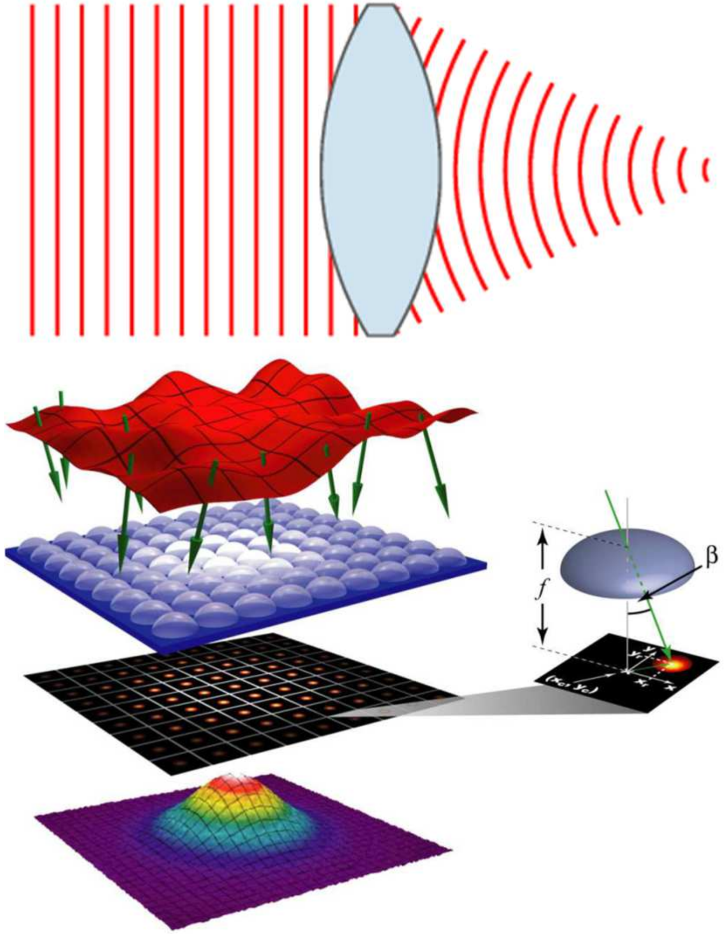
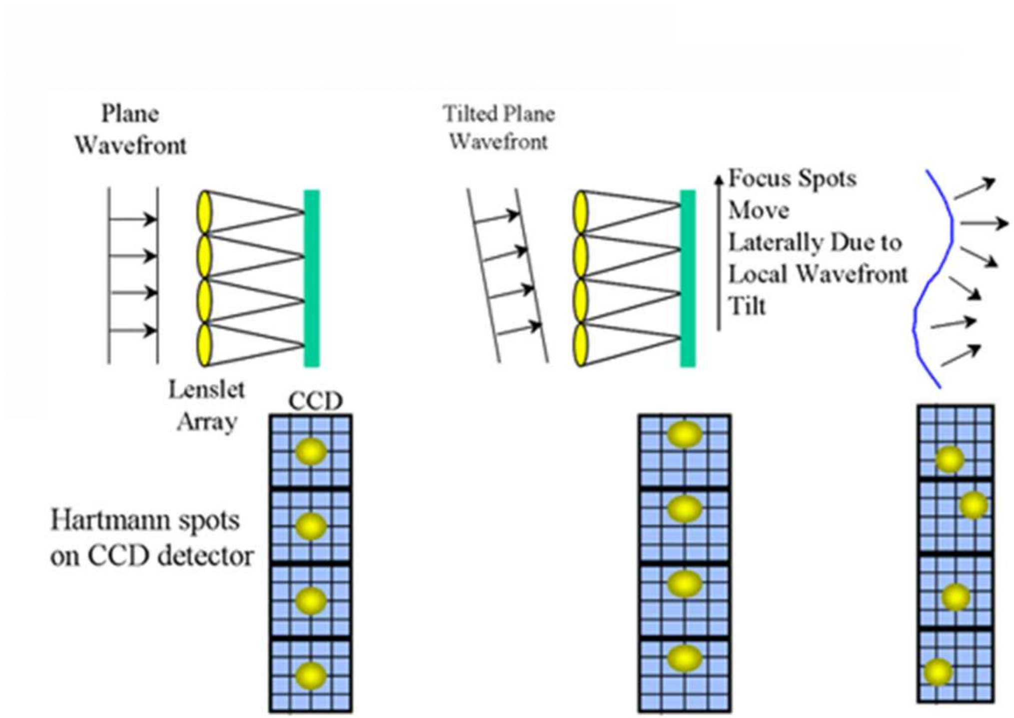
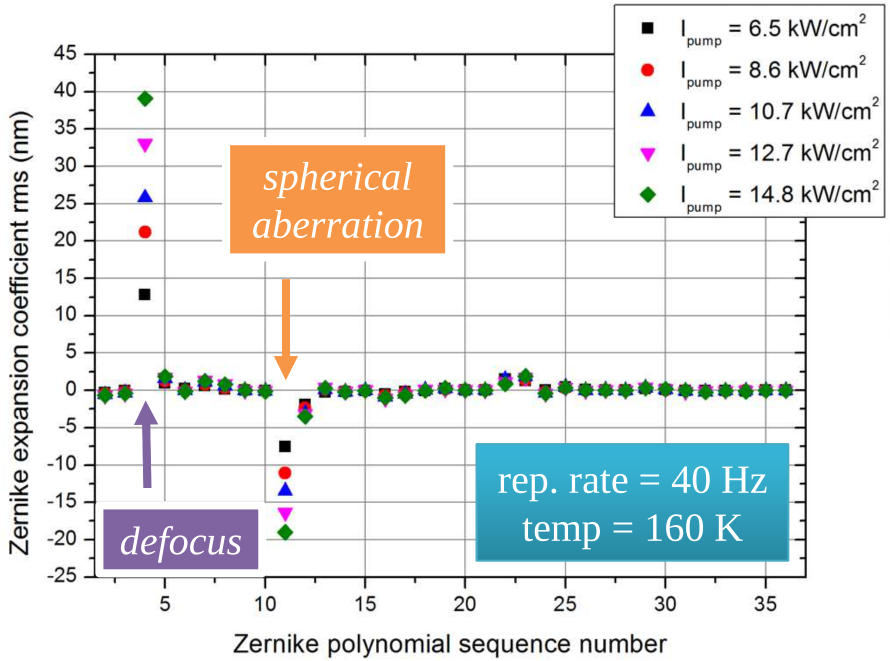
Hartmann-Shack Wavefront Analysis

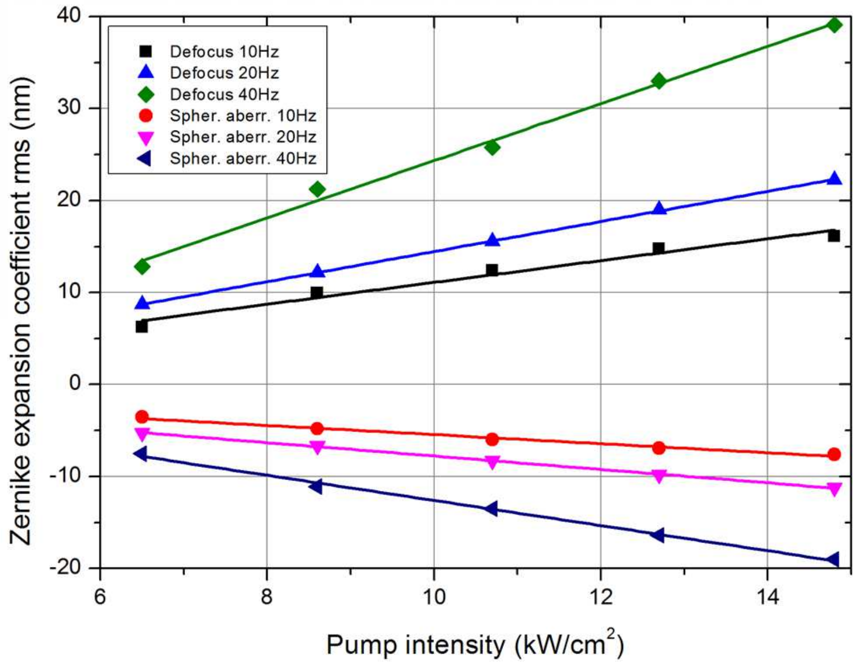




Net wavefront aberrations after 2 passes through cryogenically cooled Yb:YAG slab at different pump intensities

hilase
Power of light





At I_{pump}~14.8 kW/cm²
Spherical abberation is less than – 20 nm
what corrsponds to less than – 0.02 λ

Fyzikální ústav
Akademie věd ČR, v. v. i.
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Output energy vs input seed energy after 2 passes through the cryogenically cooled Yb:YAG slab

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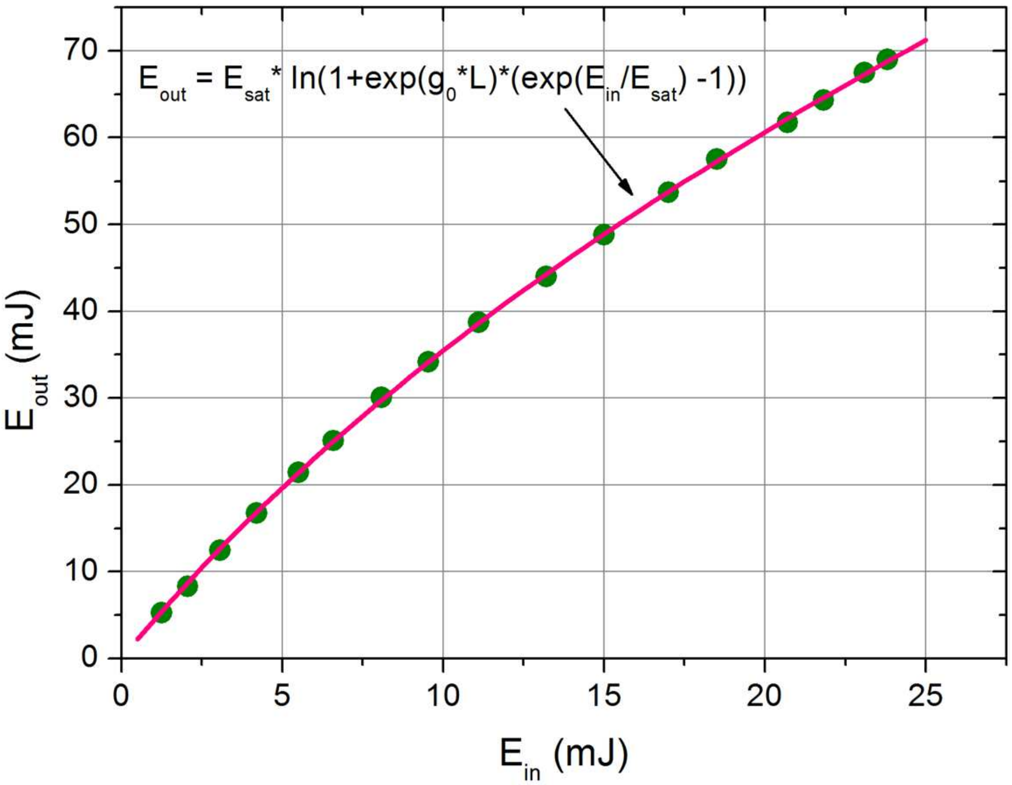

rep. rate = 40 Hz
temp = 160 K

E_{sat} = 58 mJ
$g_0 = 7.5\ cm^{-1}$

Conclusion and Perspective

Waseda University

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- Picosecond >mJ, 100kHz (>100W) laser available for pre-pulse in LPP EUV source

- >10kW EUV FEL needs advanced picosecond laser technology
  10kW, >10MHz, picosecond laser for kW 3HG, 4HG, OPCPA

- Single shot bioimaging by laser Compton source possible by cryogenic J class high beam quality picosecond laser modules in multiplexing